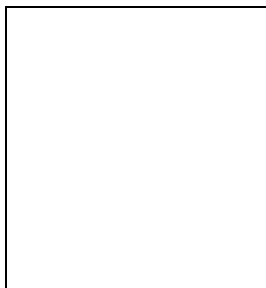


## B-Hadron Lifetimes and $\Delta\Gamma$ at the Tevatron

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We present new results on the lifetimes and widths of  $B$  hadrons based on 300-450  $\text{pb}^{-1}$  of data collected by CDF and DØ at the Fermilab Tevatron. Lifetimes were measured in semileptonic decays as well as fully reconstructed hadronic modes. A new measurement of the width difference between  $B_s$  CP eigenstates,  $\Delta\Gamma/\bar{\Gamma}$ , in  $B_s$  decays to  $J/\psi\phi$  is also presented.

### 1 Introduction

The long lifetimes of the  $B$  mesons and baryons present unique opportunities for detailed examination of heavy quark interactions and weak decays. CDF and DØ have access to the full range of  $B$  hadrons and can measure lifetimes and lifetime ratios of a variety of states in the same experiment. CDF and DØ have now analyzed 300-450  $\text{pb}^{-1}$  of  $p\bar{p}$  data at 1.96 TeV and are beginning to provide precision measurements of lifetimes of a variety of  $B$  states. Both experiments have also made first measurements of the lifetime difference between CP eigenstates,  $\Delta\Gamma/\bar{\Gamma}$ , in  $B_s$  decays to  $J/\psi\phi$ .

### 2 Lifetimes

Table 1 provides a summary of Run II lifetime measurements from Tevatron experiments prior to this conference. Lifetime ratios, which tend to have smaller experimental and theoretical errors than absolute measurements, are particularly useful in comparisons with heavy quark effective theory predictions<sup>1</sup>. These measurements represent the first lifetime data using large samples of fully reconstructed  $B_s$  and  $\Lambda_b$  decays.

DØ and CDF both use similar techniques for measuring lifetimes. Decay vertices are reconstructed with tracks selected by kinematic and mass cuts. The projection of the decay length is taken on the transverse plane ( $L_{xy}$ ). One then does a maximum likelihood fit to signal and

Table 1: Tevatron Run II  $B$  lifetime results prior to this conference.

DØ Results		CDF Results
<u>Lifetimes</u>		
$B_s^0 \rightarrow J/\psi\phi$	$1.444_{-0.090}^{+0.098} \pm 0.020$ ps <sup>3</sup>	$1.369 \pm 0.100_{-0.010}^{+0.008}$ ps <sup>6</sup>
$\Lambda_b \rightarrow J/\psi\Lambda$	$1.22_{-0.18}^{+0.22} \pm 0.020$ ps <sup>2</sup>	$1.25 \pm 0.26 \pm 0.10$ ps <sup>5</sup>
$B_c \rightarrow J/\psi\mu X$	$0.448_{-0.06}^{+0.123} \pm 0.121$ ps <sup>8</sup>	
<u>Lifetime Ratios</u>		
$\tau(B_s^0)/\tau(B^0)$	$0.980_{-0.070}^{+0.075} \pm 0.04$ <sup>3</sup>	
$\tau(\Lambda_b)/\tau(B^0)$	$0.87_{-0.14}^{+0.17} \pm 0.03$ <sup>2</sup>	
$\tau(B^+)/\tau(B^0)$	$1.080 \pm 0.016 \pm 0.014$ <sup>4</sup>	$1.119 \pm 0.046 \pm 0.014$ <sup>7</sup>

Table 2:  $B$  lifetimes measured in semi-leptonic modes.

State	Decay Mode	Lifetime or Ratio
<u>CDF</u>		
$B^-$	$l\nu D^0 X, D^0 \rightarrow K\pi$	$1.653 \pm 0.029_{-0.031}^{+0.033}$ ps
$B^0$	$l\nu D^* X, D^* \rightarrow D^0\pi$	$1.473 \pm 0.036 \pm 0.054$ ps
$\tau(B^+)/\tau(B^0)$		$1.123 \pm 0.040_{-0.039}^{+0.041}$
<u>DØ</u>		
$B_s$	$D_s\mu\nu X, D_s \rightarrow \phi\pi$	$1.420 \pm 0.043 \pm 0.057$

background lifetimes (obtained from mass sidebands) and masses including resolution functions for momenta (for partially reconstructed vertices) and decay lengths as well as a scale factor for the decay length error.

### 2.1 Lifetimes in Semileptonic Decays

Semileptonic decays typically provide large event samples with degraded momentum resolution due to the missing neutrino. DØ relies on it's muon trigger while CDF uses both muon and electron decay modes. The  $B$  decay parent is implied by reconstruction the charmed daughters. Corrections must be applied for the relative branching ratios of the  $B$  parents into the observed states. The composition of the sample must be well understood since the component decay modes have different effective momentum resolution functions ( $K$  factors).

CDF uses both electron and muon triggers in 260 pb<sup>-1</sup> of data. This sample has the advantage relative to the hadronic sample discussed in section 2.2 of having no lifetime-dependent trigger bias. The reconstructed final states are  $D^*(e \text{ or } \mu)\nu X$ , or  $D(e \text{ or } \mu)X$  with  $D \rightarrow K^-\pi^+$ . A simultaneous fit is made to both lifetime and mass distributions using the relative fractions of charged and neutral  $B$  mesons decaying to  $D$  and  $D^*$  and Monte Carlo efficiency for the reconstruction of the  $D^*$  pion. The results<sup>9</sup> are shown in Table 2. The systematic uncertainty is dominated by uncertainties in the sample composition and estimates of the prompt charm background contributions.

DØ has a new measurement of the  $B_s$  lifetime in the decay  $B_s \rightarrow D_s\mu\nu X, D_s \rightarrow \phi\pi$  in 400 pb<sup>-1</sup> of data. The fit includes calculated contamination from  $B^0, B^+$  and a momentum distribution which also includes prompt  $D_s^*$  contributions. The background at large negative lifetime comes from directly produced charm pairs with misreconstructed vertices. The mass and lifetime distributions are shown in Fig. 2. The result<sup>10</sup>, included in Table 2, is  $\tau(B_s) =$

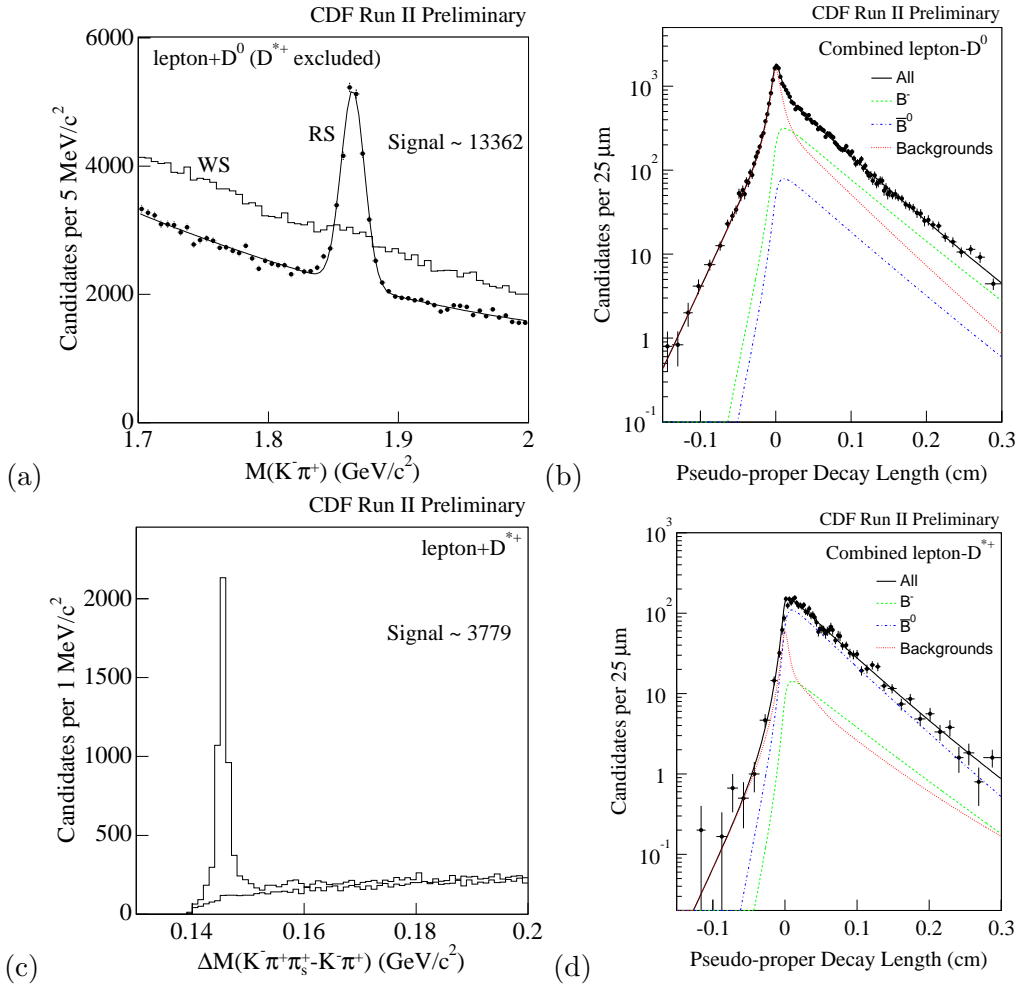


Figure 1: Mass and lifetime distributions for the  $B \rightarrow D\ell\nu X$  (a,b) and  $B \rightarrow D^*\ell\nu X$  (c,d) samples. Lines are results of the maximum likelihood fit.

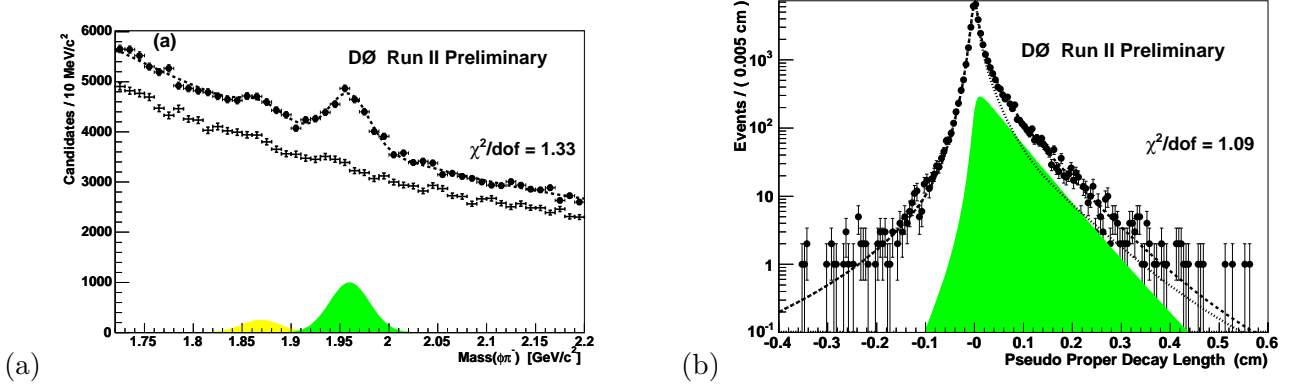


Figure 2: Mass (a) and lifetime (b) distributions for  $B_s \rightarrow D_s \mu \nu X$  from DØ with results of the likelihood fit overlaid.

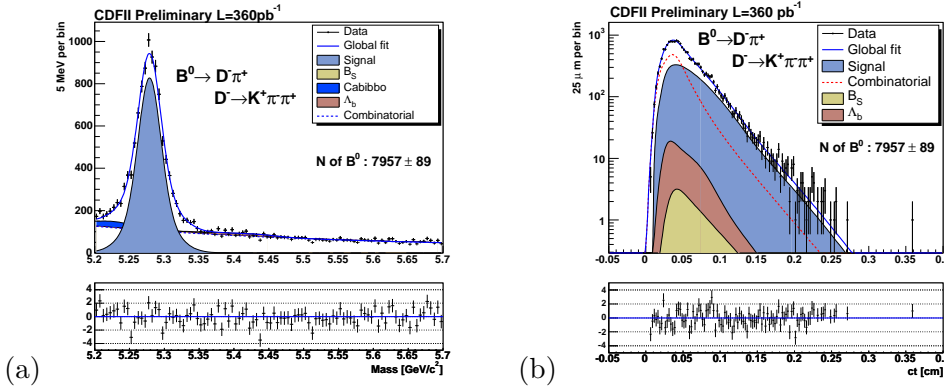


Figure 3: Mass (a) and lifetime (b) distributions for the  $B^0 \rightarrow D^- \pi^+$  mode in events triggered by the silicon vertex trigger.

$1.420 \pm 0.043 \pm 0.057$ . Systematics are dominated by the uncertainty in the extrapolation of sideband lifetimes to the  $B_s$  signal region.

## 2.2 Lifetimes in Hadronic Modes

CDF has presented first lifetime results in hadronic decay modes in data utilizing their silicon vertex trigger (SVT) in  $360 \text{ pb}^{-1}$  of data. This level 2 trigger selects events including tracks with significant impact parameters. The selection introduces a bias in the reconstructed lifetime distribution. As can be seen in Fig. 3 the lifetime distributions lack the usual prompt peak. This is corrected using a decay length and final state dependent efficiency generated by Monte Carlo and checked using charged  $B^- \rightarrow J/\psi K^-$  events triggered by dimuons from the  $J/\psi$  as well as the SVT. Typical mass and decay length distributions are shown in Figure 3. A mass-only fit using a wide mass window is first used to establish the contributions of various backgrounds. The combined mass and lifetime fit is then performed in a narrower mass range. The background proper time is modeled using the high mass sideband. The overall systematic error in these measurements is estimated to be less than  $5 \mu\text{m}$ . Results<sup>11</sup> for the five modes studied are shown in Table 3.

Figure 4 summarizes the new lifetime results from CDF and DØ for this conference along with the summer 2004 world averages compiled by the Heavy Flavor Averaging Group<sup>12</sup>. In many cases the individual lifetimes measured by Tevatron experiments are competitive with current world averages. Much of the upcoming work will concentrate on reducing systematics, which are already small in the ratio measurements, in the absolute lifetimes.

Table 3:  $B$  lifetimes measured in hadronic modes triggered by the SVT.

State	Decay Mode	Lifetime or Ratio
$B^0$	$D^- \pi^+, D^- \pi^+ \pi^- \pi^+$	$1.51 \pm 0.02 \pm 0.01$ ps
$B^+$	$D^0 \pi^+$	$1.66 \pm 0.03 \pm 0.01$ ps
$B_s^0$	$D_s^- \pi^+, D_s^- \pi^+ \pi^- \pi^+$	$1.60 \pm 0.10 \pm 0.02$ ps
$\tau(B^+)/\tau(B^0)$		$1.10 \pm 0.02 \pm 0.01$
$\tau(B_s^0)/\tau(B^0)$		$1.06 \pm 0.07 \pm 0.01$

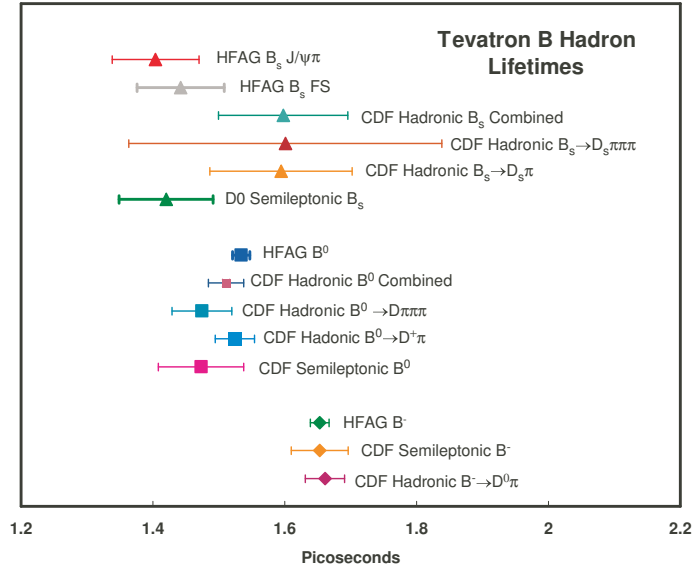


Figure 4: Summary of new lifetime measurements from CDF and DØ presented at this conference along with HFAG world average values.

### 3 Lifetime Difference in the $B_s$ System, $\Delta\bar{\Gamma}$

Mass eigenstates in the  $B_s$  system,  $B_H$  and  $B_L$ , are related to the flavor eigenstates,  $B_s^0, \bar{B}_s^0$  by:

$$\begin{aligned} B_H &= p | B_s^0 \rangle + q | \bar{B}_s^0 \rangle, \\ B_L &= p | B_s^0 \rangle - q | \bar{B}_s^0 \rangle, \\ \Delta M &= M_H - M_L, \\ \Delta\Gamma &= \Gamma_L - \Gamma_H, \bar{\Gamma} = \frac{\Gamma_L + \Gamma_H}{2}. \end{aligned}$$

Within the standard model  $B_H$  and  $B_L$  are expected to be approximate CP eigenstates ( $p \approx q$ ) with distinct lifetimes. The long-lived, heavy state is primarily CP even. The lifetime difference between these states,  $\Delta\Gamma$ , is governed by real intermediate states and has been calculated using the Heavy Quark Expansion,  $\Delta\Gamma/\bar{\Gamma} = 0.12 \pm 0.05$ <sup>13</sup>. CDF has reported a value of  $\Delta\Gamma/\bar{\Gamma} = 0.65 \pm 0.45$  in the summer of 2004<sup>14</sup>. Such a large central value, if confirmed, would be difficult to explain theoretically since new physics effects would generally tend to lower  $\Delta\Gamma$ <sup>15</sup>.

The CP content of decays of the  $B_s$  to  $J/\psi (\rightarrow \mu\mu) \phi (\rightarrow KK)$  can be analyzed by a study of the angular distributions of the decay products. The full angular distribution<sup>16</sup> involves three angles ( $\theta, \phi, \psi$ ) and a fit provides the CP even ( $A_0, A_{\parallel}$ ) and CP odd ( $A_{\perp}$ ) amplitudes as well as a phase. The CDF result fit to all three angles and provided values for all amplitudes as well as the strong phase.

DØ integrates over  $\phi$  and  $\psi$  using efficiencies derived from Monte Carlo. The "transversity" angle,  $\theta$ , which is defined in the rest frame of the  $J/\psi$  as the angle of the  $\mu^+$  with respect to the axis perpendicular to the decay plane of the  $\phi \rightarrow K^+K^-$ , is used to extract the CP information. Integration of the full angular distribution over  $\phi$  and  $\psi$  assuming flat acceptance demonstrates the relation between the amplitudes and transversity:

$$\frac{d\Gamma}{d\cos\theta} \propto \frac{3}{8} (|A_0(t)|^2 + |A_{\parallel}(t)|^2) (1 + \cos^2\theta) + \frac{3}{4} |A_{\perp}(t)|^2 \sin^2\theta.$$

DØ performs a 19 parameter fit, similar to the lifetime fits discussed above but including additional parameters for  $R_{\perp} (= A_{\perp}(0))$  and  $\Delta\Gamma/\bar{\Gamma}$ . Mass and lifetime distributions are shown in Figure 5. The result<sup>17</sup> of this fit is:

$$\begin{aligned} \bar{\tau}(B_s) &= 1.30_{-0.14}^{+0.13} \pm 0.08\text{ps}, \\ \Delta\Gamma/\bar{\Gamma} &= 0.21_{-0.40}^{+0.27} \pm 0.20, \\ R_{\perp} &= 0.17 \pm 0.10 \pm 0.02. \end{aligned}$$

This result can be improved by including measurements of the average flavor-specific  $B_s$  lifetime in semileptonic decays. The flavor-specific width is the average of the CP even and odd values. The fit to a single lifetime in semileptonic analyses results in a measured lifetime related to the mean of the CP even and odd values of:  $1/\tau_{fs} = \Gamma_{fs} = \bar{\Gamma} - (\Delta\Gamma)^2/2\bar{\Gamma} + O((\Delta\Gamma)^3/\bar{\Gamma}^2)$ . A fit using  $\bar{\tau}_{fs} = 1.43 \pm 0.05$  ps results in an improved value of  $\Delta\Gamma/\bar{\Gamma} = 0.23_{-0.17}^{+0.16}$ .

This result can also be used to provide information on the CP violating phase,  $\phi_s$ , using the relation  $\Delta\Gamma/\Gamma_{measured} = \Delta\Gamma/\Gamma_{CPconserving} \cos^2(\phi_s)$  and assuming the predicted value of  $\Delta\Gamma/\Gamma_{CPconserving} = 0.12 \pm 0.05$ . The fitted value is  $|\cos\phi_s| = 1.46_{-0.69}^{+0.73}$ . A summary of the results is shown in Figure 6.

### 4 Prospects

Both DØ and CDF have upgrades planned that will allow them to effectively trigger on and reconstruct events at the highest planned Tevatron luminosities. Tracking triggers for both experiments, which are compromised by occupancy at high luminosity, will increase in granularity.

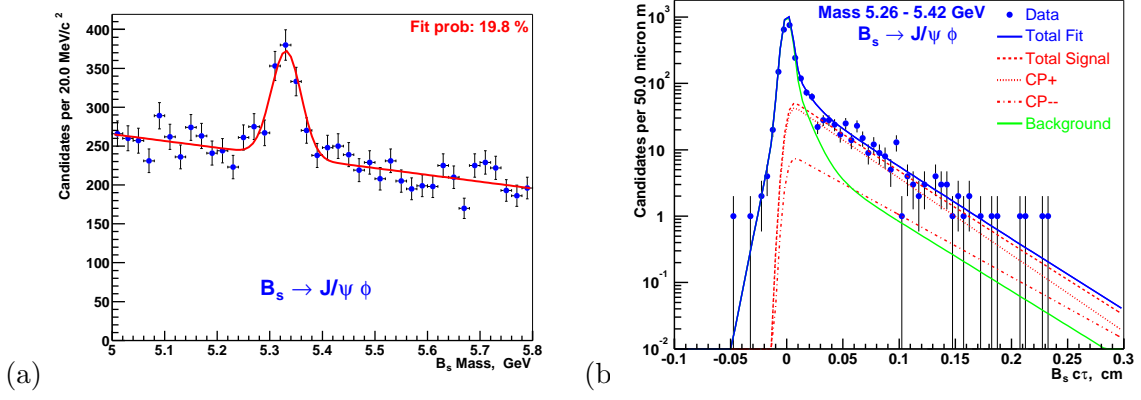


Figure 5: Mass (a) and lifetime (b) distributions for the DØ  $\Delta\Gamma$  analysis.

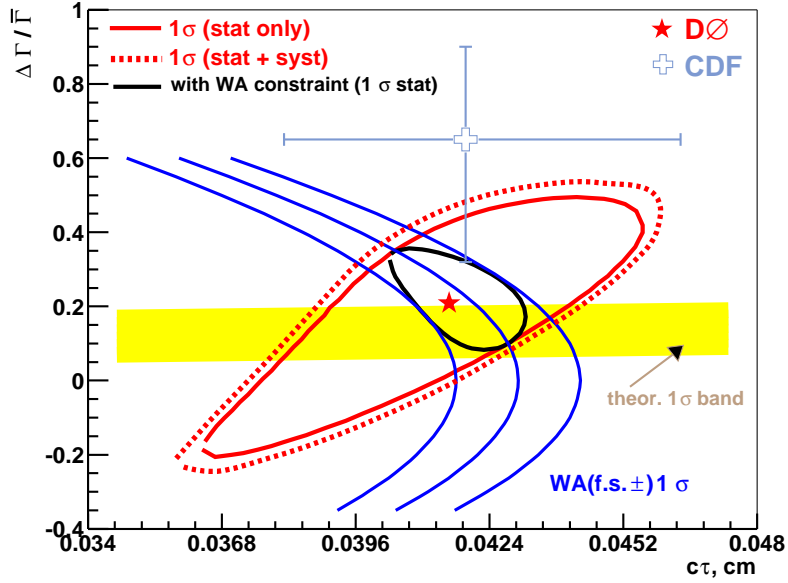


Figure 6: One  $\sigma$  contours for  $\Delta\Gamma$  plotted against fitted lifetime. Shown are the CDF (cross) and DØ (star) results, the theoretical band, and the world average lifetime constraint.

A new inner layer silicon detector for DØ similar to CDF's layer 00, located 1.6 cm from the beam, will be installed in the Fall of 2005. DØ has also proposed a DAQ rate upgrade, which will allow the experiment to increase the rate to tape from 50 to 100 Hz, with the bulk of this increase dedicated to B physics.

The Tevatron experiments have collected and analysed approximately 10% of the data set expected in Run II. With an expected order of magnitude more data, lifetimes should be measured with 1% precision.  $\Delta\Gamma$  should be measured to a few percent, and states such as  $\phi\phi$  and  $\phi K^*$  will be included in the data sample. With these data, experiments will address the detailed lifetime predictions of HQET, have sensitivity to the CP phase  $\phi_s$ , continue the search for rare decays, and extend  $B_s$  mixing measurements to the full range predicted by the standard model.

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# Tevatron B Hadron Lifetimes

